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Biomechanical comparison of knotted and knotless stabilization techniques of the tarsal medial collateral ligament in cats: A cadaveric study

Inaugural-Dissertation

zur Erlangung der Doktorwürde der
Vetsuisse-Fakultät Universität Zürich

vorgelegt von

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2020

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1 Zusammenfassung in Englisch

Abstract

The mechanical properties of intact feline medial collateral ligaments and three techniques for the treatment of feline medial tarsal instability were compared in this study.

Three repairs were tested in 48 tarsi: a bone tunnel with polypropylene suture (PP), a bone tunnel with polyethylene (PE) cord, and a knotless anchor technique with PE cord. A cyclic tensile test was performed with either the long or short medial tarsal ligament intact and each reconstruction technique followed by a load-to-failure test with a failure point at 2mm of displacement. Total elongation, peak-to-peak elongation, stiffness, and maximum load to failure point were compared to the intact condition. No differences in stiffness, total elongation, or peak-to-peak elongation were found between specimens repaired with the knotless technique and intact controls, whereas tarsi repaired with the tunnel technique and PP were weaker. Total and conditioning elongation were greater after tunnel reconstruction with PP than after knotless reconstruction. Mean load to 2mm of displacement tended to be higher after knotless PP repairs and did not differ between tunnel or anchor repairs with PE. In conclusion**,** the mechanical properties of intact feline tarsi were superior to those of tarsi repaired with tunnel techniques and PP but were similar to those of tarsi repaired with knotless techniques with PE. The knotless technique may reduce the duration for postoperative coaptation.

Keywords: feline tarsus, ligament prosthesis, biomechanical testing

2 Zusammenfassung in Deutsch

Zusammenfassung

In dieser Studie wurden die mechanischen Eigenschaften von intakten medialen Kollateralbändern des Tarsus der Katze mit drei Rekonstruktionstechniken für die mediale Tarsusinstabilität verglichen. Drei Rekonstruktionen wurden an 48 Tarsi getestet: Eine Tunneltechnik mit Polypropylenfaden (PP) oder Polyethylenfaden (PE) und eine knotenlose Ankertechnik mit PE-Faden. Ein zyklischer Zugtest wurde durchgeführt mit intaktem langem oder kurzem Kollateralband und jeder Rekonstruktionstechnik. Dem folgte ein Versagelast-Test. Totale Verlängerung, Spitze-zu-Spitze-Verlängerung, Steifigkeit und Maximallast zum Versagepunkt (VP) wurden mit dem intakten Kollateralband verglichen. Es wurde kein Unterschied in Steifigkeit, totaler und Spitze-zu-Spitze-Verlängerung zwischen den knotenlosen Rekonstruktionen und den intakten Bändern gefunden. Die Tunneltechnik mit PP-Faden war jedoch schwächer. Totale und konditionierte Verlängerung waren grösser mit Tunnelrekonstruktion und PP als mit knotenloser Technik. Der mittlere Zug bis zum VP tendierte grösser zu sein mit knotenloser Technik als mit geknoteter Technik und PP. Es lag keine Differenz zwischen knotenlosen und Tunnelrekonstruktionen mit PE vor. Zusammenfassend waren die mechanischen Eigenschaften intakter Tarsi denen mit Tunneltechnik und PP überlegen, jedoch den knotenlos reparierten Tarsi ebenbürtig. Die Stabilisation mit der knotenlosen Technik hat das Potential die Dauer postoperativer Schienung zu verkürzen.

Received: 28 March 2019 | Revised: 16 September 2019 | Accepted: 16 November 2019

DOI: 10.1111/vsu.13366

ORIGINAL ARTICLE

WILEY

Biomechanical comparison of knotted and knotless stabilization techniques of the tarsal medial collateral ligament in cats: A cadaveric study

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Abstract

Objective: To compare mechanical properties of intact feline medial collateral ligaments and three techniques for treatment of feline medial tarsal instability.

Study design: Controlled laboratory study.

Sample population: Forty-eight normal, adult feline tarsi.

Methods: Three repairs were tested: a bone tunnel with polypropylene (PP) suture, a bone tunnel with polyethylene (PE) cord, and a knotless anchor technique with PE cord. A cyclic (6-N preload; 5-N amplitude; 2-Hz frequency) tensile test (600 cycles) was performed on feline tarsi with either the long or the short medial tarsal ligament intact, with each reconstruction technique followed by a single-cycle load-to-failure test (0.5 mm/s) with a failure point at 2 mm of displacement. Total elongation, peak-to-peak elongation, stiffness, and maximum load to failure point were compared with the intact condition.

Results: No differences in stiffness, total elongation, or peak-to-peak elongation were found between specimens repaired with the knotless technique and intact controls ($P > .04$), whereas tarsi repaired with the tunnel technique and PP were weaker ($P < .008$). Total and conditioning elongation were greater after tunnel reconstruction with PP than after knotless reconstruction ($P = .005$). Mean load to 2 mm of displacement tended ($P = .03$) to be higher after knotless than after knotted PP repairs and did not differ ($P = .47$) between tarsi repaired with the tunnel or anchor repairs with PE.

Conclusion: The mechanical properties of intact tarsi were superior to those of tarsi repaired with tunnel techniques and PP but were similar to those of tarsi repaired with knotless techniques with PE.

Results from this work were presented at the 45th Annual Veterinary Orthopedic Society Conference; March 10-17, 2018; Snowmass, Colorado.

Clinical significance: Feline tarsal stabilization with the knotless technique for tarsal medial collateral ligament insufficiency may reduce the requirement for or duration of postoperative coaptation.

1 | INTRODUCTION

Injuries to the medial collateral ligaments of the tarsus are common in cats,[1-3] resulting most commonly from external rotation of the paw combined with valgus stress after blunt trauma, falls from heights, or dog bites.[4,5] A review of 531 cats with traumatic injuries reported that 88% of these injuries affected the hind limbs, the tarsus being among the most commonly injured joints.[6] In our previous retrospective study, 69% of tarsal injuries in 124 cats involved the tarsocrural joint.[7] When treated surgically, 34% of these cats underwent ligament repair. Forty-seven percent of cats required stabilization on the medial side, and 36% of cats required stabilization on the lateral side.[7] These findings are in line with findings of other studies in which the medial compartment was affected in 69% to 78% of cases.[2,3]

The primary passive stabilizers of the feline tarsus are the short tarsal collateral ligaments. The long tarsal collateral ligaments seen in dogs are lacking.[8,9] Instead, the tibialis caudalis muscle on the medial side and the fibularis brevis muscle on the lateral side contribute to tarsal stabilization during locomotion. The medial short collateral ligament in cats is subdivided into a tibiocentral (TC) part and a tibiotalar (TT) part. The TC ligament, which is located between the medial malleolus of the tibia and the dorsomedial process of the central tarsal bone, stabilizes the joint against valgus in extension. The TT ligament, which runs nearly perpendicular to the TC ligament, originates in the articular surface of the medial malleolus and inserts into the talar body. The TT ligament stabilizes the joint against valgus and rotational forces in flexion (Figure 1A).[8,11]

The goals of surgical treatment of tarsal instabilities include anatomical reconstruction of the ligaments and return to joint function.[11,12] In most cases, these goals are achieved by a combination of primary ligament repair, prosthetic ligament reconstruction, temporary joint immobilization, and controlled activity.[6,13] Prosthetic ligament reconstruction in cats is commonly achieved with bone tunnels and polypropylene (PP) knotted in a figure-of-eight pattern.[11,14] Postoperative coaptation is required to prevent premature loosening of the prosthesis before fibrosis overtakes joint stabilization.[6] However, joint immobilization is associated with high rates of morbidity, including reduced synovial fluid production, degenerative joint disease, and reduced joint range of motion.[15,16]

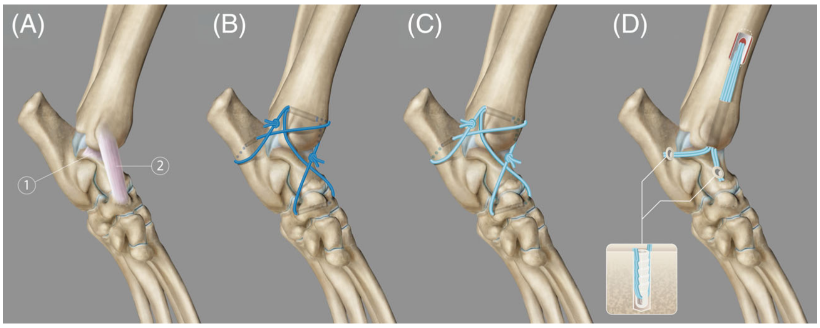

FIGURE 1 Diagram of the local anatomy and methods of repairs tested. A, Tarsal ligaments of the medial compartment. Tibiocentral ligament (2) located between the medial malleolus and the dorsomedial process of the central tarsal bone and stabilizing the joint against valgus in extension. Tibiotalar ligament (1) originates medially, from the articular surface of the medial malleolus, and inserts on the talar body. This ligament runs nearly perpendicular to the TC ligament and stabilizes the joint against valgus in flexion. B, Reconstruction of the tarsal medial collateral ligaments with the tunnel technique according to Nicholson et al.[11] The TC and TT ligaments are reconstructed separately. Bone tunnels are drilled close to the origin and insertion points of the ligaments, one into the medial malleolus of both ligaments, a second into the calcaneus of the TT ligament, and a third into the central tarsal bone of the TC ligament. Polypropylene suture material (B) or bone tunnels (C) similarly located compared with B. Polyethylene cord is passed through the bone tunnels and knotted in a figure-of-eight pattern. D, Knotless anchor technique. A biceps button loaded with four strands of suture material is inserted into the distal tibial medullary canal. The suture material is shuttled through a vertical bone tunnel in the distal tibia. Two strands of suture material are then attached to the talar body with a suture anchor to reconstruct the TC part of the medial collateral ligament. Likewise, two strands of suture material are attached to the calcaneus to reconstruct the TT part. Permission for use of Figure 1B and D obtained from M&H Schaper GmbH.[10] TC, tibiocentral; TT, tibiotalar

A new knotless technique for the reconstruction of the medial tarsal collateral ligaments in cats in which low-profile bone anchors and nonabsorbable multifilament ultra–high-molecular-weight polyethylene cord (PE) are used was recently developed.[17] This technique was developed with the goal of achieving sufficient stiffness and strength to allow its application without postoperative coaptation.[18] Such a technique for tarsal ligament reconstruction may be advantageous because of the risk of complications and poor tolerability associated with bandages in cats.[19-21]

Our primary objective was to biomechanically compare (1) a knotless anchor reconstruction technique, (2) a bone tunnel reconstruction technique, and (3) the intact ligaments. Our second objective was to compare the biomechanical properties of two prosthetic materials, PP and PE, used for the bone tunnel technique. We hypothesized that the knotless anchor reconstruction technique (1) would be stiffer and have less elongation compared with the bone tunnel reconstruction technique and (2) would be no different from the intact ligament. In addition, we hypothesized that a bone tunnel technique combined with PE cord would be biomechanically superior to a tunnel technique combined with PP.

2 | MATERIALS AND METHODS

2.1 | Specimen preparation

Paired hind limbs were harvested from 32 skeletally mature cats (weight range, 1.96-8 kg) that had been euthanized for reasons unrelated to the study. The anatomic specimens were collected according to the regulations of the University of Zurich and with owner permission. Fluoroscopy images were obtained to evaluate skeletal maturity as well as to exclude specimens with skeletal pathologies. The limbs were wrapped in towels soaked in physiologic saline (0.9% NaCl) solution and stored in a freezer at −20°C until the day of testing.

On the day of mechanical testing, the specimens were thawed to room temperature, and muscles and tendons were removed from the bone. The joint capsule and all additional tissues that could not be removed completely were cut at the level of the tarsocrural joint. However, the ligament to be tested (TC or TT part) was left intact. Forty-eight tarsi were randomly assigned to one of eight groups on the basis of (1) the ligament to be tested (TC or TT) and (2) treatment (intact ligament, bone tunnel with PP, bone tunnel with PE, and knotless bone anchor technique; Table 1). One band was transected, while the other was left intact for testing (TC or TT), depending on the testing group. The tibia, fibula, and metatarsi were all osteotomized at the level of the middiaphysis. Each distal tibia was then placed in the center of a 60-mm-long and 52-mm-diameter segment of acrylic glass pipe and embedded in beracryl-monomere (SCS-Beracryl D-28 monomer; Swiss-Composite, Fraubrunnen, Switzerland). The same process was repeated for potting the metatarsi. Here, Kirschner wires (K-wires) were placed for extra stability. One wire was placed into the fourth metatarsal bone and through the tarsometatarsal and intertarsal joints into the distal calcaneus, and two cross pins were placed into the talocalcaneal joints, not entering the talocrural joint (Figure 2).

2.2 | Surgical technique

2.2.1 | Bone tunnel technique

Three 1.5-mm-diameter bone tunnels were drilled as described by Nicholson et al[11]; tunnel 1 was drilled

TABLE 1 Experimental design

Group	Ligament tested	Surgical technique	Sample size, n	Test
ILTT	Intact tibiotalar	Control	6	Cyclic
ILTC	Intact tibiocentral	Control	6	Cyclic
PPTT	Reconstructed tibiotalar	Tunnel with PP	6	Static and cyclic
PPTC	Reconstructed tibiocentral	Tunnel with PP	6	Static and cyclic
PETT	Reconstructed tibiotalar	Tunnel with PE	6	Static and cyclic
PETC	Reconstructed tibiocentral	Tunnel with PE	6	Static and cyclic
BATT	Reconstructed tibiotalar	Knotless anchor	6	Static and cyclic
BATC	Reconstructed tibiocentral	Knotless anchor	6	Static and cyclic

Abbreviations: BATC, reconstructed tibiocentral anchor; BATT, reconstructed tibiotalar anchor; ILTC, intact tibiocentral; ILTT, intact tibiotalar; PE, polyethylene; PETC, reconstructed tibiocentral tunnel polyethylene cord; PETT, reconstructed tibiotalar tunnel polyethylene cord; PP, polypropylene; PPTC, reconstructed tibiocentral tunnel polypropylene; PPTT, reconstructed tibiotalar tunnel polypropylene; TC, tibiocentral; TT, tibiotalar.

through the medial malleolus in the craniocaudal direction, tunnel 2 was drilled in the central tarsal bone in the dorsoplantar direction, and tunnel 3 was drilled in the proximal calcaneus in the mediolateral direction (Figure 1B,C [see also Figure 5]). After specimens had been mounted in the testing machine, PP USP 0 (Premilene, 3.5 metric; B Braun Medical AG, Sempach, Switzerland) or PE suture material USP 0 (Fiberwire, 3.5 metric; Arthrex GmbH, Munich, Germany) was inserted in a figure-of-eight pattern between tunnels 1 and 2 or between tunnels 1 and 3 for the reconstruction of the TC and TT part of the ligament, respectively. The TC and TT sutures were tightened the tarsus was being held at 180° and 90° joint angles, respectively. All of the knots were hand-tied by a trained surgeon (S.C.K.) with a surgeon's knot and four additional knots before testing. Specimens had already been mounted in the testing apparatus when sutures were tied. Tightness was controlled manually by palpation of the construct, and tightening was repeated in case the sutures subjectively appeared loose, as performed during surgical procedures in clinical cases.

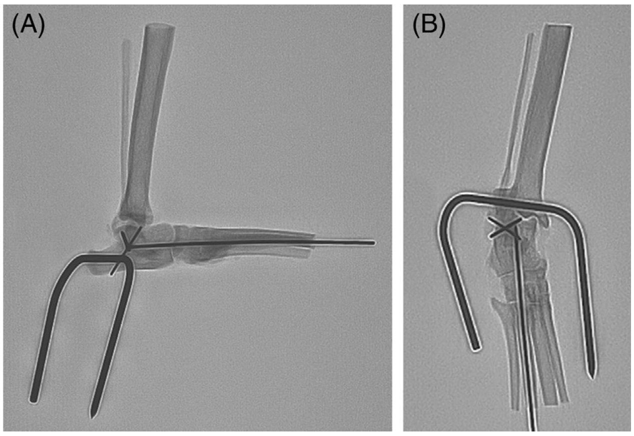

FIGURE 2 Specimen preparation. A, Fluoroscopic images were obtained to evaluate skeletal integrity of the joints. In addition, the joints were reinforced with Kirschner wires. One wire was placed into Mt 4 and through the tarsometatarsal and intertarsal joints into the distal calcaneus. Two cross pins were placed into the talocalcaneal joints, not entering the talocrural joint. B, One large pin was inserted into the proximal calcaneus and bent in position to be embedded in beracryl-monomere together with the metatarsal bones

2.2.2 | Knotless anchor technique

The knotless anchor technique was performed as previously described.[18] In brief, a 3.5-mm-diameter unicortical tunnel was drilled in the medial cortex of the distal tibia at an angle of 30° relative to the tibial cortex in a proximal direction (Figures 1D and 3). A 1.2-mm-diameter tunnel was drilled in the medial malleolus at the footprint of the origin of the medial collateral ligaments in the proximal direction. A biceps button was loaded with four strands of PE (Fiberwire, 3.5 metric/USP 0; Arthrex GmbH) and inserted into the unicortical hole in the tibia. Then the suture material was shuttled through the vertical tunnel in the medial malleolus to the footprint of the ligament.

For the reconstruction of the TT ligament, a hole was drilled into the calcaneus in a plantarodistal direction with a 2-mm drill bit, and the transcortex was overdrilled with a 2.5-mm drill bit. For the TC ligament, the tunnel

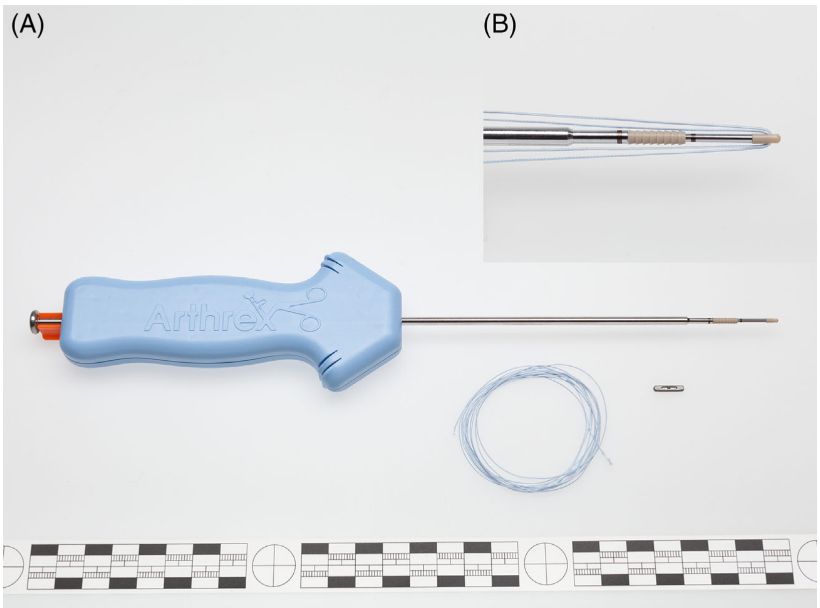

FIGURE 3 A, Photograph of the devices used for the knotless technique: bone anchor, suture material, and suture button. B, The bone anchor is loaded with four strands of polyethylene cord before insertion

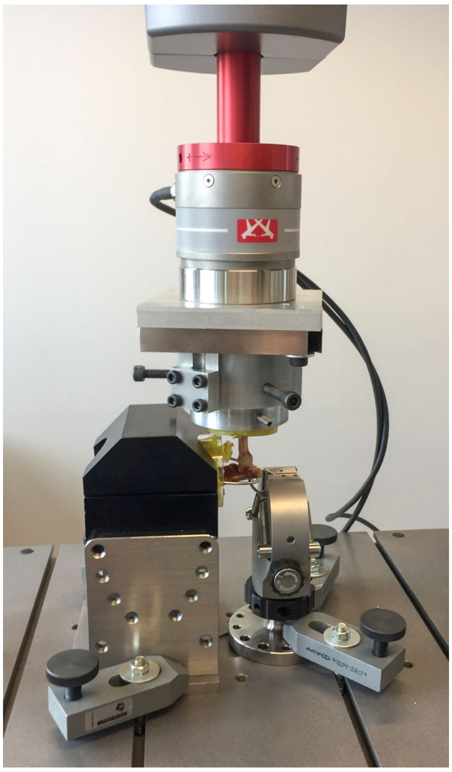

FIGURE 4 Mounting of the specimen in the material testing machine. Pure cyclic or static tensile load was applied from the load actuator above the specimen

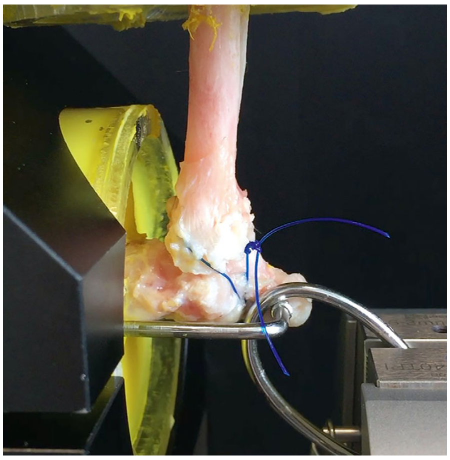

FIGURE 5 Reconstructed (polypropylene) tibiotalar ligament mounted in the material testing machine at 90° of flexion

was drilled in the talar body in a dorsodistal direction with a 2-mm drill bit, and the transcortex was overdrilled with a 2.5-mm drill bit, as previously described.[18] The distal fixation of the suture was performed with an interference bone anchor made of polyetheretherketone (Mini PEEK PushLock, 2.5 × 8 mm; Arthrex GmbH) for the reconstruction of the TT or TC ligaments. Before bone anchors were irreversibly inserted in the bone, tightness was tested by the surgeon (S.C.K.) by palpation of the suture material. Ligament tightness was evaluated subjectively and applied similarly in each construct.

TABLE 2 Variables tested under cyclic and tensile loading to test repair elongation and strength

Outcome measurements	Description
Total elongation, mm	Displacement change from baseline displacement before applying any preload to maximum displacement after 600 cycles
Peak-to-peak elongation, mm	Difference in displacement for the construct at the 600th cycle while applying an amplitude of 5 N
Conditioning elongation, mm	Difference in displacement between the peak of the first stable cycle and the 600th peak during cyclic loading
Stiffness, N/mm	Stiffness for cyclic loads was measured at 150 cycles; stiffness for load-to-failure tests was measured within the first mm of actuator displacement
Maximum load to 2 mm of displacement, N	Load measured at 2 mm of suture material elongation

2.3 | Mechanical testing

The biomechanical testing of the six groups with reconstruction techniques (Table 1) included pure tensile cyclic and static load testing with a servohydraulic material testing system (ElectroPlus E3000; Instron, Norwood, Massachusetts) equipped with a 5-kN load cell (Instron) attached to the actuator (Figure 4). A custom-made fixation device was used to consistently align the tibia with the load actuator to ensure that the tensile load was applied in the long axis of the tibia. The foot was positioned in either a 90° flexion angle to test the TT ligament or a 180° extended angle to test the TC ligament (Figure 5). Pilot testing was performed to validate the setup and to calculate the sample size.

Cyclic testing was performed with a preload of 6 N followed by 600 cycles with 5-N amplitude at 2 Hz (load control) to determine the peak-to-peak, conditioning, and total elongation and stiffness (N/mm; Table 2).[17,19] Applied load ranged from 0% to 20% body weight (10 N, loaded from 1-11 N) to simulate the weight-bearing forces during

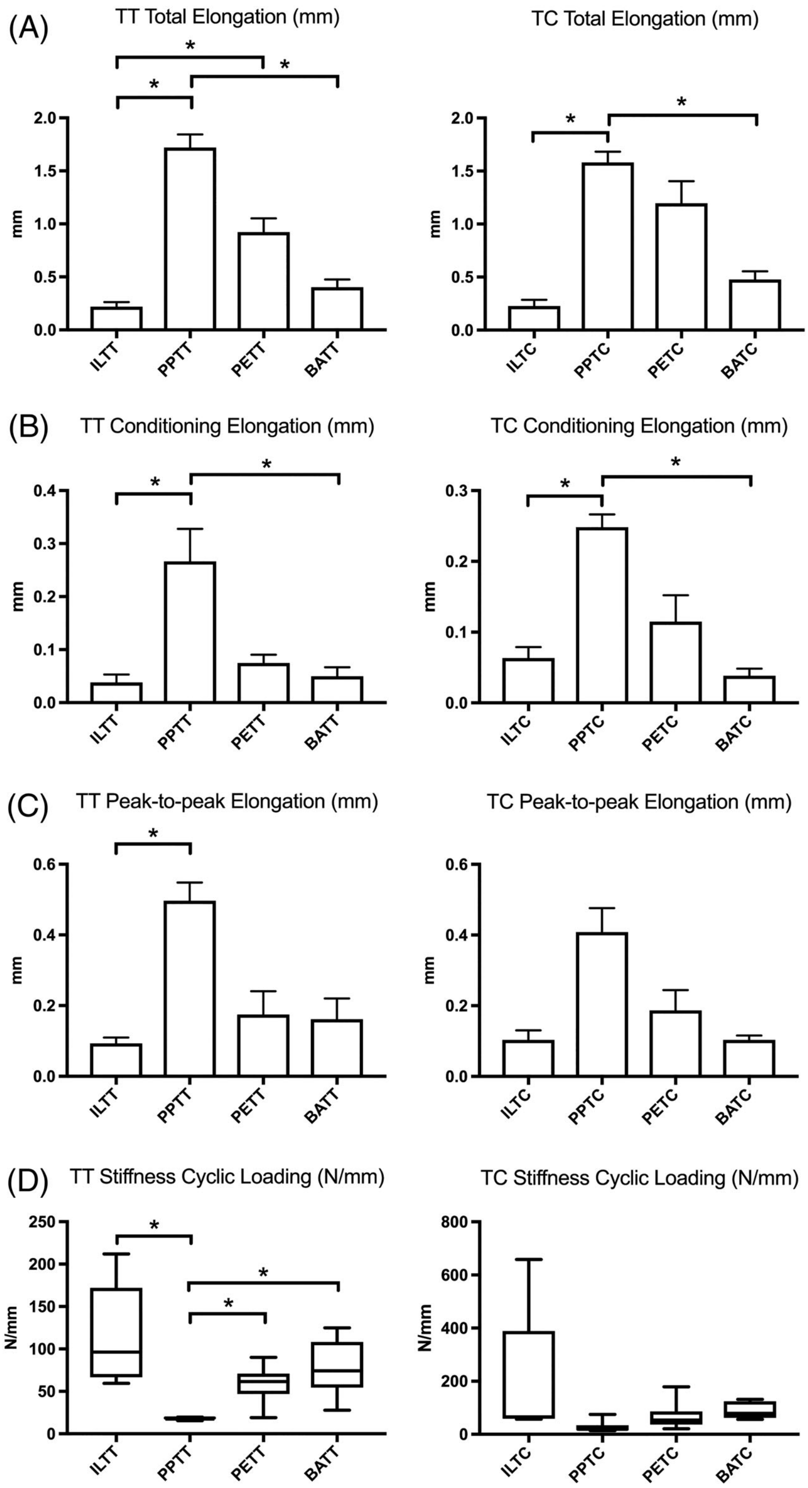

FIGURE 6 Histograms (mean ± SEM) of total elongation (A), conditioning elongation (B), and peak-to-peak elongation in cyclic loading (C). D, Boxplots of stiffness in cyclic loading (5th-95th percentile). $*P < .008$, difference between linked groups after Bonferroni correction. BATC, reconstructed tibiocentral anchor; BATT, reconstructed tibiotalar anchor; ILTC, intact tibiocentral; ILTT, intact tibiotalar; PETC, reconstructed tibiocentral tunnel polyethylene cord; PETT, reconstructed tibiotalar tunnel polyethylene cord; PPTC, reconstructed tibiocentral tunnel polypropylene; PPTT, reconstructed tibiotalar tunnel polypropylene; TC, tibiocentral; TT, tibiotalar

walking.[22] After completion of the cyclic testing, all specimens were loaded to failure at a rate of 0.5 mm/s. Failure was defined as 2 mm of displacement or catastrophic failure. The definition of failure at 2 mm of displacement was based on a displacement measured from stress radiographs of cats with clinically relevant medial tarsal instability.

Specimens with intact ligaments (groups ILTT and ILTC) underwent the same cyclic and static loading as described for the reconstruction techniques. They were used as controls for the analysis. Outcome measurements were calculated separately for cyclic loading and load-to-failure tests and are presented in Table 2.

TABLE 3 Biomechanical tests for tibiotalar ligaments

Outcome Measure, Unit	1, ILTT	2, PPTT	3, PETT	4, BATT
Total elongation, mm	0.22 ± 0.11	1.72 ± 0.30 $P_{1\text{-}2} = .0051$*	0.92 ± 0.32 $P_{1\text{-}3} = .0051$* $P_{2\text{-}3} = .0131$	0.40 ± 0.18 $P_{1\text{-}4} = .0453$ $P_{2\text{-}4} = .0051$* $P_{3\text{-}4} = .0131$
Conditioning elongation, mm	0.04 ± 0.04	0.27 ± 0.15 $P_{1\text{-}2} = .0082$*	0.08 ± 0.04 $P_{1\text{-}3} = .1735$ $P_{2\text{-}3} = .0202$	0.05 ± 0.04 $P_{1\text{-}4} = .3785$ $P_{2\text{-}4} = .0082$* $P_{3\text{-}4} = .2890$
Peak-to-peak elongation, mm	0.09 ± 0.04	0.50 ± 0.13 $P_{1\text{-}2} = .0051$*	0.18 ± 0.16 $P_{1\text{-}3} = .2298$ $P_{2\text{-}3} = .0306$	0.16 ± 0.14 $P_{1\text{-}4} = .5211$ $P_{2\text{-}4} = .0202$ $P_{3\text{-}4} = .6889$
Stiffness cyclic loading, N/mm	115.38 ± 59.24	17.87 ± 1.78 $P_{1\text{-}2} = .0051$*	58.86 ± 22.86 $P_{1\text{-}3} = 0.0656$ $P_{2\text{-}3} = 0.0082$*	77.93 ± 33.37 $P_{1\text{-}4} = .3785$ $P_{2\text{-}4} = .0051$* $P_{3\text{-}4} = .1735$
Max load to 2 mm of displacement, N	80.35 ± 14.87	20.74 ± 2.12 $P_{1\text{-}2} = .0051$*	44.37 ± 16.08 $P_{1\text{-}3} = .0051$* $P_{2\text{-}3} = .0051$*	37.61 ± 12.25 $P_{1\text{-}4} = .0051$* $P_{2\text{-}4} = .0306$ $P_{3\text{-}4} = .4712$
Stiffness load to failure, N/mm	42.02 ± 9.61	11.20 ± 0.94 $P_{1\text{-}2} = .0051$*	30.83 ± 6.36 $P_{1\text{-}3} = .0656$ $P_{2\text{-}3} = .0051$*	56.77 ± 20.62 $P_{1\text{-}4} = .0927$ $P_{2\text{-}4} = .0051$* $P_{3\text{-}4} = .0306$

Note: Values are mean ± SD.
Abbreviations: BATT, reconstructed tibiotalar anchor; ILTT, intact tibiotalar; PETT, reconstructed tibiotalar tunnel polyethylene cord; PPTT, reconstructed tibiotalar tunnel polypropylene.
*$P < .008$, difference between linked groups after Bonferroni correction.

2.4 | Data analysis

A power analysis was performed after pilot testing to calculate the sample size. Descriptive statistics and plots were calculated for each group and used to check for spurious observations and data consistency. Pairwise comparisons were planned ahead of data collection, obviating the requirement for an omnibus statistical test.[23] Certain pairs of groups were tested by using the nonparametric Wilcoxon rank-sum test. Although Bonferroni correction was not required for planned comparisons, as an extra layer of caution it was used to adjust for type-1 error inflation within tests for each variable. Statistical significance was set by the Bonferroni correction at $P < .008$. In some comparisons, the groups shared some limbs from the same animals, violating the assumption of independence across groups. A separate correlation analysis provided evidence that the impact of the shared limbs was negligible. Statistical analysis was performed in Prism (GraphPad Software, San Diego, California).

3 | RESULTS

Mean body weight of the cadavers was 4.41 ± 1.39 Kg. There was no difference in body weight among the eight groups ($P > .05$).

3.1 | Cyclic loading

Polypropylene groups had the highest mean total and conditioning elongation, except for groups PETT and PETC (Figure 6, Tables 3 and 4). Peak-to-peak elongation was higher for the PPTT group compared with the intact ligament (Table 3). However, peak-to-peak elongation in PP groups did not reach significance compared with the other groups (Figure 6). There was no difference between the tunnel technique with PE and the intact ligaments for peak-to-peak elongation (Tables 3 and 4). In knotless groups, mean ± SD stiffness was not different from intact ligaments.

TABLE 4 Biomechanical tests for tibiocentral ligaments

Outcome Measure, Unit	1, ILTC	2, PPTC	3, PETC	4, BATC
Total elongation, mm	0.23 ± 0.15	1.58 ± 0.25 $P_{1\text{-}2}$ = .0051*	1.20 ± 0.52 $P_{1\text{-}3}$ = .0306 $P_{2\text{-}3}$ = .1282	0.48 ± 0.19 $P_{1\text{-}4}$ = .0453 $P_{2\text{-}4}$ = .0051* $P_{3\text{-}4}$ = .0656
Conditioning elongation, mm	0.06 ± 0.04	0.25 ± 0.05 $P_{1\text{-}2}$ = .0051*	0.12 ± 0.09 $P_{1\text{-}3}$ = .2980 $P_{2\text{-}3}$ = .0306	0.04 ± 0.02 $P_{1\text{-}4}$ = .2298 $P_{2\text{-}4}$ = .0051* $P_{3\text{-}4}$ = .1735
Peak-to-peak elongation, mm	0.10 ± 0.06	0.41 ± 0.17 $P_{1\text{-}2}$ = .0396	0.19 ± 0.14 $P_{1\text{-}3}$ = .1087 $P_{2\text{-}3}$ = .1087	0.10 ± 0.03 $P_{1\text{-}4}$ = .5752 $P_{2\text{-}4}$ = .0131 $P_{3\text{-}4}$ = .1087
Stiffness cyclic loading, N/mm	200.82 ± 243.28	27.42 ± 23.61 $P_{1\text{-}2}$ = .0306	67.38 ± 56.20 $P_{1\text{-}3}$ = .0306 $P_{2\text{-}3}$ = 0.0656	88.77 ± 31.61 $P_{1\text{-}4}$ > .99 $P_{2\text{-}4}$ = .0202 $P_{3\text{-}4}$ = .0656
Max load to 2 mm of displacement, N	103.98 ± 19.06	22.74 ± 2.88 $P_{1\text{-}2}$ = .0051*	50.83 ± 20.69 $P_{1\text{-}3}$ = .0131 $P_{2\text{-}3}$ = 0.0051*	50.32 ± 10.21 $P_{1\text{-}4}$ = .0051* $P_{2\text{-}4}$ = .0051* $P_{3\text{-}4}$ = .4712
Stiffness load to failure, N/mm	49.39 ± 14.31	12.11 ± 1.93 $P_{1\text{-}2}$ = .0051*	22.15 ± 18.45 $P_{1\text{-}3}$ = .0245 $P_{2\text{-}3}$ = .5745	37.11 ± 10.05 $P_{1\text{-}4}$ = .2298 $P_{2\text{-}4}$ = .0051* $P_{3\text{-}4}$ = .0450

Note: Values are mean ± SD.
Abbreviations: BATC, reconstructed tibiocentral anchor; ILTC, intact tibiocentral; PETC, reconstructed tibiocentral tunnel polyethylene cord; PPTC, reconstructed tibiocentral tunnel polypropylene.
*$P < .008$, difference between linked groups after Bonferroni correction.

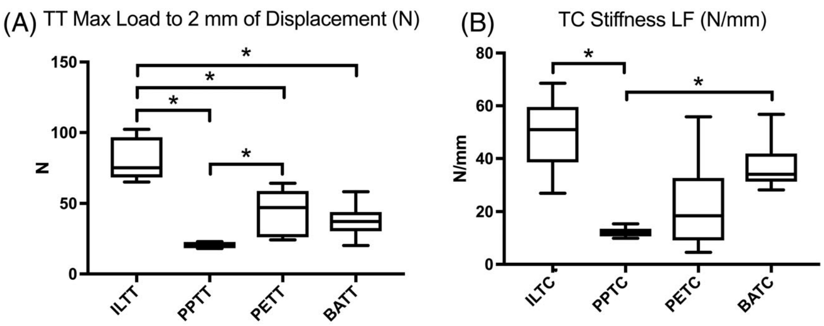

FIGURE 7 A, Maximum load to 2 mm of displacement in TT ligaments (5th-95th percentile). B, Stiffness in load-to-failure testing of TC ligaments (5th-95th percentile). *$P < .008$, difference between linked groups after Bonferroni correction. BATC, reconstructed tibiocentral anchor; BATT, reconstructed tibiotalar anchor; ILTC, intact tibiocentral; ILTT, intact tibiotalar; PETC, reconstructed tibiocentral tunnel polyethylene cord; PETT, reconstructed tibiotalar tunnel polyethylene cord; PPTC, reconstructed tibiocentral tunnel polypropylene; PPTT, reconstructed tibiotalar tunnel polypropylene; TC, tibiocentral; TT, tibiotalar

3.2 | Load to failure

The knotless reconstructed (BA) TC anchor group withstood higher mean maximum loads to 2 mm of displacement compared with the knotted PPTC group (Table 4). The same trend was seen in TT ligaments (Figure 7A and Table 3). Knotless BA groups resisted loads that were similar to the knotted PE groups (Figure 7A, Tables 3 and 4). Mean stiffness of intact ligaments and knotless groups was higher than in PP groups ($P < .008$) (Figure 7B, Tables 3 and 4). The knotted repairs consistently failed through suture breakage away from the knot, usually at the proximal or distal and medial tunnel ridges. The failure mode of the knotless repair technique was suture slippage between anchor and bone in six of 12 cases, anchor pullout in four of 12 cases, and suture slippage with subsequent anchor pullout in two of 12 cases.

4 | DISCUSSION

Our results provide evidence supporting the conclusion that the knotless anchor repair of medial collateral tarsal ligaments in cats has biomechanical characteristics that approximate the intact ligament's mechanical properties. These results may support a clinical evaluation of this technique with a shortened postoperative phase of coaptation. On the other hand, tunnel techniques have limitations such as excessive elongation and low stiffness, which may require a standard time period of postoperative coaptation until sufficient periarticular fibrosis is achieved. These results should be confirmed in a clinical trial because an ex vivo study design with a limited number of cycles does not replicate the physiologic loads that may be responsible for failure of the reconstruction.

4.1 | Suture material

The tunnel technique with PP resulted in the highest total and conditioning elongation as well as the lowest stiffness of all groups. This result was expected because PP is a highly elastic material with a low stiffness that undergoes plastic deformation early during loading. Braided PE, on the other hand, is much stiffer and more resistant to plastic deformation.[14,17,24] The difference that we found between PP and PE is in line with the results achieved by Jordan et al[14] in comparing PP to PE. The applied loads used in the Jordan et al[14] study were higher, and the suture material was thicker than in our study, explaining the difference in ultimate forces.[14]

4.2 | Knotted vs knotless

Knotted PP groups had higher total and conditioning elongation compared with the knotless anchor prosthesis groups in our study. The same trend for elongation was seen when comparing the knotted PE vs the knotless group, even though significance could not be shown. We used elongation as our primary outcome measure in cyclic loading because it corresponds to the clinical scenario of progressive failure of the repair. Total elongation includes the slack of the system and any initial loosening of the prosthesis when applying a preload, which simulates a cat bearing weight immediately after a prosthetic repair has been performed. This initial loosening of the construct due to knot tightening or slippage might be sufficient to cause failure of the repair and instability.

Our results provide evidence confirming that knot tightening increases the risk of elongation in cyclic loading.[17,25,26] Knot security depends on the suture materials and the tension applied to the suture.[17,24] In our study, the braided knotted group performed better than the monofilament group, providing evidence confirming the results of other studies in which braided suture materials were investigated.[17,24] Applying and maintaining tension was more difficult in the knotted tunnel technique than in the knotless technique, as we noted subjectively. We found that an advantage of the knotless technique is that it allows one to test stability before final implantation of the anchor. In contrast, the knotted technique does not allow assessment of stability before completing the reconstruction.

4.3 | Load to failure

Knotted PE and knotless groups withstood similar loads, corresponding to approximately 100% of a cat's body weight. This value is much higher than the ground-reaction forces of a single limb during walking in a 5-kg cat but most likely lower than in a cat jumping or running. When the cat jumps to a maximum height, this load can increase about four to five times, which corresponds to 40 to 50 N.[27] This amount of load is shown to be tolerated by the previously discussed groups, including the knotless technique group, and, therefore, the load to failure should not be a limiting factor when evaluating coaptationless techniques. If they are managed properly, cats should be exercise restricted (eg, not be able to jump to their maximum achievable heights postsurgery). Maximum forces acting on the tarsus should remain in lower ranges that might allow a coaptationless approach. However, PP groups withstood loads significantly lower than 40 to 50 N; this, again, provides evidence for the requirement for external coaptation.

4.4 | Limitations of the study

The most important limitation of the study is the nonphysiologic ex vivo study design. Despite attempting to simulate in vivo cycling, it remains difficult to extrapolate our results to clinical cases and fully support a coaptationless technique without additional in vivo studies. We used a limited number of unpaired legs per group. Because eight groups were formed, the overall number of legs was still ample. The tarsus is extremely complex, with 13 bones, five main joints, and several small bone connections involved.[8] Reinforcement of all joints except the talocrural joint was challenging, and minimal slack might have remained. Bone tunnels were all drilled by the same board-certified surgeon (S.C.K.) in the anatomic locations previously described.[11] However, minimal differences in tunnel position could have influenced our results. To facilitate test setup and interpretation of results, we tested the two ligaments separately and applied pure tensile load to test the specimen as an accepted biomechanical testing setup.[17,28,29] Clinical settings will challenge the prosthesis in additional directions, with rotational, axial, and bending forces that were not assessed in this study. Furthermore, the two parts of the prosthesis applied together could potentially synergize, leading to more stable constructs. Also, a limited number of cycles were applied to the constructs. Because most elongation (eg, through knot slippage) occurred early in the cycling protocol, 600 cycles were considered sufficient.

4.5 | Clinical relevance

In summary, the knotless anchor prosthesis for the cat's tarsal medial collateral ligaments provides a biomechanically advantageous method compared with commonly used tunnel techniques for the treatment of tarsal instabilities. Case selection is critical, and we recommend the knotless technique for closed tarsal instabilities in which no open soft-tissue injuries are present. This is because of the higher risk for infection associated with contaminated injuries and the use of multifilament suture material.[30-34] In combination with the promising clinical results that were achieved in a different study,[18] our study results lead us to propose a clinical evaluation with the new knotless technique with a shorter phase of postoperative coaptation. Furthermore, the prognosis given to medial collateral ligament instability might be improved by reducing postoperative coaptation and allowing earlier return to function. Long-term prospective clinical studies are required to test complication rates and outcomes as well as a direct comparison to established techniques.

ACKNOWLEDGMENT

We thank Pascal Glatzfelder and Michelle Oesch from scientific communications and publicity (Vetcom), Vetsuisse Zurich, Zurich, Switzerland for providing their graphic support for the figures presented in this article.

CONFLICT OF INTEREST

The implants were donated by Arthrex. The authors (S.P., A.P., A.G., S.C.K.) work as part-time consultants for Arthrex.

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How to cite this article: Luescher M, Schmierer PA, Park BH, et al. Biomechanical comparison of knotted and knotless stabilization techniques of the tarsal medial collateral ligament in cats: A cadaveric study. *Veterinary Surgery*. 2019; 1–11. https://doi.org/10.1111/vsu.13366

4 Danksagung

Hiermit bedanke ich mich herzlichst bei meinen Betreuern Sebastian Knell und Antonio Pozzi, sowie Philipp Schmierer, Andreas Gutbrod und Brian Park und dem ganzen Chirurgie-Team für die Möglichkeit mit Ihnen diese Dissertation zu erarbeiten. Es war eine Bereicherung mit solch engagierten Leuten zusammenarbeiten zu dürfen. Ein grosses Dankeschön geht auch an die Abteilung Vetcom mit Pascal Glatzfelder, Jeanne Peter und Michelle Aimée Oesch für die wunderschönen Illustrationen im Paper.

Zudem danke ich besonders meiner lieben Familie und meinen Freunden, dass sie mir während meiner Dissertationszeit moralisch beiseite standen.

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